Magnetic behaviors of (Ga,Mn)As/Co$_2$FeAl Bilayers grown by molecular-beam epitaxy

S. H. Nie$^{1,2}$, L. Chen$^1$, K. K. Meng$^1$, X. Z. Yu$^1$, L. J. Zhu$^1$, W. S. Yan$^3$, Y. G. Zhao$^{2}$ and J. H. Zhao$^{1,*}$

$^1$State Key Laboratory for Superlattices and Microstructures, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
$^2$State Key Laboratory of Low-Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084, China
$^3$National Synchrotron Radiation Laboratory, University of Science & Technology of China, Hefei 230029, China

*Email: jhzhao@red.semi.ac.cn

1. Introduction

As a model of diluted ferromagnetic semiconductors, (Ga,Mn)As has attracted a great deal of attention in recent years due to its potential to spintronic devices. However, the highest Curie temperature ($T_C$) of (Ga,Mn)As so far is 191 K, still well below room temperature for practical application [1]. One of the most promising ways to solve this problem is utilizing a magnetic proximity effect at the interface of ferromagnetic metal/ferromagnetic semiconductor heterostructures [2-4], which not only offers the prospect of combining metal-based spintronics with semiconductor spintronics, but also creates new functions and physical phenomena. In addition, the relative magnetization state of two magnetic layers can be controlled without the spacer layer as compared with the traditional magnetic devices, which brings us much benefit in technology application [5]. Recently, Olejnık et al. investigated magnetic properties of Fe/(Ga,Mn)As bilayers, demonstrating an exchange bias in (Ga,Mn)As film induced by antiferromagnetic coupling to the Fe film [4]. Heusler alloy Co$_2$FeAl is one of the most promising spintronic materials because of its high spin polarization and high $T_C$. Recent studies have shown that epitaxial Co$_2$FeAl films grown on GaAs (001) have in-plane uniaxial magnetic anisotropy with an easy axis along the [110] direction, while for heavily Mn-doped (Ga,Mn)As films grown on GaAs (001), the easy axis is along the [1-10] direction [6]. Therefore, the investigation of Co$_2$FeAl/(Ga,Mn)As bilayers may offer an access to new functionalities in spintronics and physical phenomena.

2. Experiments

In this work, we present a detailed examination of the structure and magnetic properties of (Ga,Mn)As/Co$_2$FeAl bilayers grown on (GaAs) (001) by molecular-beam epitaxy. The 150 nm-thick (Ga,Mn)As films with Mn concentration from 1 to 5% have been grown in one chamber of a molecular-beam epitaxy (MBE, V80) with two growth chambers. The growth rate and substrate temperature were 10 nm/min and 250 $^\circ$C, respectively. Subsequently the samples were transferred via a high vacuum channel to the other MBE growth chamber for Co$_2$FeAl evaporation. Reference samples were obtained by dipping Fe/(Ga,Mn)As into a HCl solution to remove Co$_2$FeAl layer. The well ordered surfaces were verified by in situ reflective high-energy electron diffraction (RHEED) observation. Finally samples were covered by a 2 nm-thick epitaxial Al layer to prevent oxidation. X-ray diffraction measurements and high-resolution cross-sectional transmission electron microscopy (HRTEM) have shown the single-crystalline structure of both layers as well as a sharp interface between them. Temperature dependence of the remanent magnetization showed $T_C$ of the (Ga,Mn)As film is 80 K.

We acquired x-ray circular magnetic dichroism (XMCD) spectra at the Co, Fe and Mn L edges at National Synchrotron Radiation Laboratory (Hefei, China). XMCD measurements have proved the ferromagnetic state of Mn element at the interface at room temperature, indicating magnetic proximity effect up to room temperature as shown in Fig. 1. The magnetic anisotropy axis of both Co$_2$FeAl and (Ga,Mn)As layers was determined by a superconducting quantum interference device.

[Fig. 1 XMCD spectra of Mn $L_{2,3}$, normalized to the $L_3$ peak of the summed spectra for Co$_2$FeAl/(Ga,Mn)As bilayers.]
magnetometer (SQUID). Hysteresis loops of (Ga,Mn)As/Co$_2$FeAl bilayers were measured at 5 K under the external magnetic field along the [110] and [1-10] directions as shown in Fig. 2. It is noted that the magnetic behaviors of (Ga,Mn)As/Co$_2$FeAl bilayers strongly depend on the exchange coupling between them.

![Hysteresis loops of Co$_2$FeAl/(Ga,Mn)As bilayers at 5 K. The external magnetic field was applied along the [110] and [1-10] directions.](image)

3. Conclusions

(Ga,Mn)As/Co$_2$FeAl bilayers were well grown on GaAs (001) by molecular-beam epitaxy. Consistent with previous studies on Fe/(Ga,Mn)As of other groups, the interface layer of (Ga,Mn)As also remains spin polarized up to room temperature, which induced by heusler alloy Co$_2$FeAl. GaMnAs/Co$_2$FeAl heterostructures may be a good choice of MTJ. We also presented a detailed study on magnetic anisotropies of GaMnAs/Co$_2$FeAl bilayers.

Acknowledgements

We gratefully acknowledge H. L. Wang, S. L. Wang and P. F. Xu for their help on sample preparation, and H. H. Zhou for HRTEM measurements. This work is supported in part by the National Natural Science Foundation of China under Grant Nos. 60836002, 10920101071 and the National Basic Research of China No. 2007CB924903.

References